

DELAY-LOCKED LOOP (DLL) INTEGRATED CIRCUITS HAVING HIGH BANDWIDTH AND RELIABLE LOCKING CHARACTERISTICS

Field of the Invention

The present invention relates to integrated circuit devices and, more particularly, to integrated circuit devices having clock generators therein and methods of generating clock signals.

Background of the Invention

5 Phase-locked loop (PLL) and delay-locked loop (DLL) integrated circuits are frequently used to generate highly accurate internal clock signals on integrated circuit substrates (e.g., chips). However, such conventional PLL and DLL integrated circuits are frequently susceptible to unwanted clock skew and jitter as clock speed and circuit integration levels are increased. In particular, PLLs typically suffer from phase error
10 accumulation that may persist for long periods of time in noisy environments, whereas DLLs may have lower jitter performance because phase error accumulation does not occur. Thus, DLLs may offer an important alternative to PLLs in cases where a reference clock signal comes from a low-jitter source. However, DLLs typically cannot be used in
15 applications where frequency tracking is required, such as frequency synthesis and clock recovery. DLLs may also be difficult to design for environments that experience significant process, voltage and temperature (PVT) variations.

The operating frequency range of conventional DLLs is also frequently limited because DLLs adjust only phase and not frequency. For example, the conventional DLL **10** of FIG. 1 may be limited to a relatively narrow frequency range of operation. As illustrated, the DLL **10** includes a voltage-controlled delay line (VCDL) **12**, which generates an output clock signal DLLCLK in response to a reference clock signal REFCLK, a phase detector (PD) **14**, charge pump (CP) **16** and a loop filter (LF) **18** that generates an analog control voltage V_c . This control voltage V_c is provided as a bias signal to a plurality of identical delay elements **15**. When the delay time (T_{VCDL}) of the VCDL **12** is initially shorter (or longer) than the period (T_{CLK}) of the reference clock signal REFCLK, the DLL **10** automatically adjusts the delay time T_{VCDL} until a phase difference between the reference clock signal REFCLK and the output clock signal DLLCLK is eliminated. This phase difference is detected by sampling the reference clock signal REFCLK with the rising edges of the output clock signal DLLCLK, which is provided as a feedback clock signal. This sampling is performed by the phase detector **14**, which generates UP or DOWN pulses that are provided to the charge pump **16**. These pulses charge (or discharge) a capacitor in the loop filter **18**, thereby decreasing (or increasing) the control voltage V_c and gradually reducing the phase difference by adjusting the delay of the delay elements **15**.

Unfortunately, the performance of the DLL **10** of FIG. 1 may be limited by a stuck or harmonic lock problem. To avoid this problem, the minimum delay time ($T_{VCDL-min}$) of the VCDL **12** should be located between $\frac{1}{2}T_{CLK}$ and T_{CLK} and the maximum delay time ($T_{VCDL-max}$) of the VCDL **12** should be located between T_{CLK} and $1.5T_{CLK}$. These relationships result in a maximum range of T_{CLK} as follows: $0.667(T_{VCDL-max}) < T_{CLK} < T_{VCDL-max}$, where $T_{VCDL-max} = 2T_{VCDL-min}$. However, if $T_{VCDL-max} \geq 3T_{VCDL-min}$, there is no range of T_{CLK} that meets these conditions and the DLL **10** becomes prone to the stuck problem. Because the PVT variations associated with the delay time T_{VCDL} can be as much as 2:1 in a typical CMOS process, the stuck-free

condition can be satisfied over only a very narrow range of T_{CLK} when the DLL **10** of FIG. 1 is used.

To address these problems associated with conventional DLLs, analog DLLs that utilize replica delay lines have been proposed. For example, FIG. 2 illustrates an analog DLL **20** having a main delay line (within a core DLL) and a replica delay line (RDL) **26** therein. The main delay line includes a plurality of delay elements **25** that generate an output clock signal DLLCLK. This output clock signal DLLCLK is provided as a feedback clock signal to a phase detector **14'**, which also receives a reference clock signal REFCLK. The core DLL also includes a charge pump **16'** and a loop filter **18'**, which generates a fine-tune control voltage V_{cp} . The delay provided by the main delay line is controlled primarily by a control voltage V_{cr} that is generated by the replica delay line **26**. The replica delay line **26** consists of a single replica delay cell **25'**, a current steering phase detector (CSPD) **22** and a low-pass filter (LPF) **24**. Because of a sharing of the control voltage V_{cr} , the delay time of the replica delay cell **25'** is almost equal to the delay time of each of the delay elements **25** in the main delay line. The delay time of the replica delay cell **25'** will equal the delay time of each of the delay elements **25** in the main delay line if the fine-tune control voltage V_{cp} equals the bias voltage BIAS. If the current steering phase detector **22** is designed appropriately, the delay time of the replica delay cell **25'** can be made to equal one-eighth the period (T_{CLK}) of the reference clock signal REFCLK. Accordingly, the delay provided by the main delay line will equal T_{CLK} when the number of delay elements **25** in the main delay line equals eight. In this manner, the wide frequency range of the replica delay line **26** will translate to a core DLL having well established operating frequency bounds and generally stuck-free operation. The DLL **20** of FIG. 2 is more fully described in an article by Y. Moon et al, entitled "An All-Analog Multiphase Delay-Locked Loop Using a Replica Delay Line for Wide-Range Operation and Low-Jitter Performance," IEEE Journal of Solid State Electronics, Vol. 25, No. 3, pp. 377-384, March 2000. Unfortunately, this DLL **20** will typically not lock

when the minimum delay of the main delay line plus any fixed delay in the main feedback path is greater than the clock period. Moreover, the use of a replica delay line requires the use of an additional charge pump, which can significantly increase the area and power consumption requirements of the DLL.

Thus, notwithstanding these conventional DLLs, therein continues to be a need for alternative DLLs having stuck-free operation and high degrees of jitter immunity.

Summary of the Invention

Integrated circuit devices according to embodiments of the present invention include delay-locked loops (DLLs) having wide frequency range operation and reduced clock jitter characteristics. These DLLs utilize a portion of a full feedback loop to set an initial locking state upon start-up and then switch over to a full feedback loop locking condition that is less susceptible to relocking in response to PVT variations. In particular, the DLLs are configured to support transition from a partial feedback loop lock condition to a full feedback loop lock condition during a start-up time interval. These DLLs include a variable delay line and a fixed delay line that collectively form a full feedback path. An auxiliary phase detector and a main phase detector are utilized to provide a temporary partial loop locking condition that is followed by a full loop locking condition that is maintained throughout the course of normal operation (i.e., when the clock signal at the output of the DLL is valid). The auxiliary phase detector has first and second inputs that are connected to ends of a auxiliary delay line that contained within the variable delay line. During start-up, the auxiliary phase detector operates to increase the delay of the delay elements within the variable delay line until the auxiliary delay line becomes locked. The auxiliary phase detector is then disabled at the same time that the main phase detector is enabled. Once enabled, the main phase detector seeks to lock the full feedback loop to multiple cycles of the reference clock. This simultaneous switching-off of the auxiliary phase detector and switching-on of the main phase detector operates to jump the lock condition from a

partial cycle condition to a multiple cycle lock condition and thereby skip a full cycle lock condition which may be prone to relocking in response to PVT variations.

Brief Description of the Drawings

5 FIG. 1 is an electrical schematic of a delay-locked loop (DLL) according to the prior art.

 FIG. 2 is an electrical schematic of a delay-locked loop (DLL) according to the prior art.

 FIG. 3A is an electrical schematic of a delay-locked loop (DLL) according to an embodiment of the present invention.

 FIG. 3B is a timing diagram that illustrates operation of the DLL of FIG. 3A.

Detailed Description of Preferred Embodiments

15 The present invention now will be described more fully herein with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as being limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like reference numerals refer to like elements throughout and signal lines and signals thereon may be referred to by the same reference characters. Signals may also be synchronized and/or undergo minor boolean operations (e.g., inversion) without being considered different signals.

25 Referring now to FIG. 3A, a delay-locked loop (DLL) **30** according to an embodiment of the present invention includes a variable delay line **40** that is responsive to a reference clock signal (REFCLK). This variable delay line is illustrated as having a plurality of variable delay stages **35** (shown as N stages). As will be understood by those skilled in the art, the delay provided by these stages **35** may be controlled by a control voltage (V_C) having a magnitude that may fluctuate within a range defined between minimum and maximum control voltages. The DLL is configured to

generate a clock signal DLLCLK that is provided as an output clock signal and as a feedback clock signal to a main phase detector (PDA) **50a**. A fixed delay line **45** is provided between the variable delay line **40** and an output of the DLL **30**. The fixed delay line **45** may be defined by a plurality of elements (e.g., input clock buffer, output clock buffer, clock tree, etc.) that collectively provide a relatively fixed delay to a periodic signal generated at an output of the variable delay line **40**. As described herein, the variable delay line **40** and the fixed delay line **45** collectively define a full feedback loop that extends from a first input of the main phase detector **50a**, which receives the reference clock signal REFCLK, to a second input of the main phase detector **50a** that receives the feedback clock signal (DLLCLK).

The DLL **30** further includes an auxiliary phase detector **50b** having first and second inputs that are electrically connected to respective delay stages **35** within the variable delay line **40**. As illustrated, the variable delay line **40** includes M delay stages **35** that define an auxiliary delay line **42**. The first delay stage **35** in the auxiliary delay line **42** has an input that is electrically coupled to a first input (IN1) of the auxiliary phase detector **50b** and the last delay stage **35** in the auxiliary delay line **42** has an output that is electrically connected to a second input (IN2) of the auxiliary phase detector **50b**.

The main phase detector **50a** is configured to generate UPA and DOWNA signals (pulses) in response to detecting phase differences between the reference clock signal REFCLK and the feedback clock signal DLLCLK. The main phase detector **50a** may constitute a three-state phase frequency detector of conventional design. The auxiliary phase detector **50b** is configured to generate UPB and DOWNB signals (pulses) in response to detecting phase differences between the clock signals provided to the input and generated at the output of the auxiliary M-stage delay line **42**. As described more fully hereinbelow, the auxiliary phase detector **50b** may constitute an edge-triggered set-reset type (SR-type) phase detector. A multiplexer **60** is provided between the main and

auxiliary phase detectors **50a** and **50b** and a charge pump (CP) **70**, as illustrated. The multiplexer **60** is responsive to a select signal (shown as SELPD). When the select signal SELPD is set to a first logic level (e.g., logic 1), the signals UPA and DOWNA are provided to the charge pump **70**.
5 However, when the select signal SELPD is set to a second logic level (e.g., logic 0), the signals UPB and DOWNB are provided to the charge pump **70**. The charge pump **70** is configured to drive a low pass filter (LPF) **80** using conventional techniques. In some embodiments, the generation of an UP pulse at the input of the charge pump **70** results in an increase (or
10 decrease) in the magnitude of the control voltage V_C and the generation of a DOWN pulse at the input of the charge pump **70** results in a decrease (or increase) in the magnitude of the control voltage V_C .

As will now be described more fully with reference to FIGS. 3A-3B, the DLL **30** operates by forcing the total delay line (i.e., the series
15 combination of the variable delay line and the fixed delay line) to lock to two cycles of the reference clock signal REFCLK over a wide range of reference clock frequencies. As will be understood by those skilled in the art, if $t_{VAR(min)} + t_{FIXED} > T_{REFCLK}$ (where $t_{VAR(min)}$ represents the minimum delay provided by the variable delay line **40**, t_{FIXED} represents the delay provided
20 by the fixed delay line **45** and T_{REFCLK} is the period of the reference clock signal REFCLK), then the DLL **30** will lock to two cycles of the reference clock signal REFCLK. However, if $(t_{VAR(min)} + t_{FIXED} < T_{REFCLK})$, then the DLL **30** will lock to one cycle of the reference clock signal REFCLK when the auxiliary phase detector **50b** is not utilized during start-up (i.e., during initial
25 power-on or after reset). Accordingly, if the DLL **30** of FIG. 3A is utilized in the absence of the auxiliary phase detector **50b** during start-up and is required to operate under both of these conditions, then there is a critical reference clock period where $t_{VAR(min)} + t_{FIXED} = T_{REFCLK(crit)}$. When this occurs, the DLL **30** will lock to either one cycle or two cycles of the
30 reference clock signal REFCLK. This condition is undesirable in many applications because if the DLL initially locks to one cycle (or two cycles) in the feedback path, then for varying power supply voltages and

temperatures (where the delay of the fixed delay line **45** can vary), the DLL may re-lock to two cycles (or one cycle) or have excessive phase jitter.

To address this problem, the auxiliary phase detector **50b** is used during start-up to set up a two cycle lock condition that can be maintained over a wide frequency range. Other forced lock conditions (e.g., 3-cycle lock) are also possible in alternative embodiments. This forced locking is achieved by using an auxiliary phase detector **50b** to influence the value of the control voltage V_C upon start-up (e.g., initial power-on or upon reset) and establish an intermediate locking state, before switching from the auxiliary phase detector **50a** to the main phase detector **50b** to establish a final locking state that can be supported over a wide frequency range. As illustrated by FIG. 3B, this "two-stage" locking sequence is commenced by switching a power-on reset signal (PO_RESET) from an active high level to an inactive low level to commence DLL operation. While the power-on reset signal PO_RESET is set high, the control circuit **90** in FIG. 3A operates to hold the low pass filter **80** in a reset mode. This causes the control voltage V_C to be held at level sufficient to set the delay of the delay elements **35** in the variable delay line **40** at a minimum value (e.g., $V_C = V_{dd}$). As this is happening, both the main and auxiliary phase detectors **50a-50b** and the charge pump **70** are disabled.

Once the power-on reset signal PO_RESET switches to an inactive low level (i.e., once a trailing edge of PO_RESET is detected by the control circuit **90**), the auxiliary phase detector **50b** is enabled and the multiplexer **60** is set to select the output signals UPB and DOWNB for output to the charge pump **70**. By designing the auxiliary phase detector **50b** as an edge-triggered SR-type phase detector, the M-stage auxiliary delay line **42**, which represents just a portion of the full feedback loop, will lock to half a cycle of the reference clock signal REFCLK. In alternative embodiments, the portion of the full feedback loop defined by the auxiliary delay line can be locked to a full cycle of the reference clock signal REFCLK.

Based on an appropriate ratio of the length M of the auxiliary delay line **42** to the length N of the variable delay line **40**, a half cycle lock

condition at the inputs of the auxiliary phase detector **50b** will cause the inputs (IN1 and IN2) of the main phase detector **50a** to be offset by greater than 1.5 cycles of the reference clock signal REFCLK and less than 2.5 cycles of the reference clock signal REFCLK. Once the M-stages of the auxiliary delay line **42** are locked to half a clock cycle, the auxiliary phase detector **50b** is disabled and the main phase detector **50a** is enabled. The control circuit **90** performs this operation by simultaneously switching the reset signal RSTPDB low-to-high, switching the reset signal RSTPDA high-to-low and switching the select signal SELPD low-to-high to thereby cause the output signals UPA and DOWNA to be passed to the charge pump **70**. This allows the main phase detector **50a** to then lock the full feedback loop, which includes the variable delay line **50** and the fixed delay line **45**, to two cycles of the reference clock signal REFCLK.

The point at which the auxiliary phase detector **50b** is switched over to the main phase detector **50a** is performed synchronously with the reference clock signal REFCLK. In particular, if the main phase detector **50a** locks to the rising edges of its inputs, then the switch over is performed in-sync with a falling edge of the reference clock signal REFCLK, however, if the main phase detector **50a** locks to the falling edges of its inputs, then the switch over is performed in-sync with a rising edge of the reference clock signal REFCLK. This insures that the first UPA pulse or DOWNA pulse out of the main phase detector **50a** causes the full feedback loop to lock to two cycles of the reference clock signal REFCLK. The number of cycles of the reference clock signal REFCLK during which the auxiliary phase detector **50b** is enabled in response to a reset event, is inversely proportional to the loop bandwidth of the auxiliary DLL loop (elements **42**, **50b**, **60**, **70** and **80**). Thus, a higher bandwidth requires fewer numbers of cycles of the reference clock signal REFCLK during which the auxiliary phase detector **50b** is enabled.

The auxiliary phase detector **50b** should be kept enabled for a sufficient number of cycles (i.e., X cycles) of the reference clock signal REFCLK to insure a lock condition, as illustrated by FIG. 3B, where X may

equal about 128 cycles in some embodiments. In this manner, the enablement of the main phase detector **50a** is timed to a count of a number of cycles of the reference clock signal REFCLK. In alternative
 5 control circuit **90** to detect when the auxiliary delay line **42** is locked. Upon detection of a lock condition, the auxiliary phase detector **50b** and the lock detector circuit would be disabled and the main phase detector **50a** would be enabled.

The number of delay elements **35** required in the variable delay line
 10 **40** is a function of the minimum clock pulse width associated with the reference clock signal REFCLK. In the illustrated embodiment, the length of the variable delay line **40** equals $8(T_{REFCLK}/t_{PUL})$, where t_{PUL} is the minimum high or low pulse width of the reference clock signal REFCLK. For a reference clock signal having a 50% duty cycle, $N=16$. This number
 15 of stages will allow the full feedback loop to lock to two cycles with minimum duty cycle distortion. The number M of delay elements **35** in the auxiliary delay line **42** is determined by the value of the delay provided by the fixed delay line **45**, which may represent a collection of elements (e.g., input clock buffer, output clock buffer, tree and dummy register delays). In
 20 particular, the value of M is set so that when the auxiliary delay line **42** becomes locked, the total delay around the main feedback loop does not exceed 2.5 clock cycles at the minimum period of the reference clock signal REFCLK (i.e., maximum clock frequency). This value of M can be determined by solving equation (1):

$$\frac{1}{2}(N(T_{REFCLK}(\min))/M) + t_{FIXED} < \frac{1}{2}(5T_{REFCLK}(\min)) \quad (1)$$

The maximum period of the reference clock signal (i.e., minimum clock frequency) can then be determined from equation (2):

$$\frac{1}{2}(N(T_{REFCLK}(\max))/M) + t_{FIXED} < \frac{1}{2}(3T_{REFCLK}(\max)) \quad (2)$$

Based on these relationships, if the period of the reference clock signal REFCLK exceeds $T_{\text{REFCLK}}(\text{max})$, then the DLL 30 will lock to only one cycle of the reference clock signal REFCLK when the main phase detector 50a is enabled. This result is acceptable because $T_{\text{REFCLK}}(\text{max})$ is much greater than $T_{\text{REFCLK}}(\text{crit})$ and typical variations in power supply voltage and temperature will not cause the DLL 30 to relock (e.g., from two cycles to one cycle) or have excessive clock jitter.

In the drawings and specification, there have been disclosed typical preferred embodiments of the invention and, although specific terms are employed, they are used in a generic and descriptive sense only and not for purposes of limitation, the scope of the invention being set forth in the following claims.